Building Component Lifecycle Repair/Replacement Model for Institutional Facility Management

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Abstract

The building infrastructure operations and maintenance phase is usually the longest and most costly phase of a building's lifecycle, ultimately exceeding the total cost of initial design and construction. Targeting these operations and maintenance costs and the cumulative sustainment and renewal costs can have a significant effect on reducing total cost of ownership. This requires planning and correct timing of work, to reduce the adverse affect of deferred maintenance and repair which lead to accelerated deterioration and restoration costs for the structure. There is thus a financial payback in terms of reduced lifecycle cost for correcting distresses and maintaining a quality condition level through proactive facility management.

This paper will examine the work management practices necessary to reduce total lifecycle cost of ownership for building facilities using a computational component repair/replacement simulation model. This model incorporates condition measurement, condition prediction, component service life expectancies, and corrective repair/replacement scenarios. Examples will show how a best practice approach to facility management can lower total maintenance and repair costs by nearly half over 50-year lifecycle.

Building Infrastructure Lifecycle

Buildings are comprised of systems and components, crossing civil, mechanical, and electrical construction disciplines. Each component works interdependently with other components to support the functions of an efficiently operating building. As a physical asset, these components age and deteriorate over time, ultimately adversely affecting performance and reliability of the building. Certain components, such as structural columns, have a service life designed to correspond to the life of the facility. Other components, such as a roof surface, can have a design life much shorter than the life of the facility. The lifespan of a component is rarely known exactly, and actual service life depends greatly on local environmental factors, use and abuse, and levels of routine maintenance accomplished. Periodic repair or replacement of the various deteriorated components is needed to restore condition and performance capabilities for the component and the building as a whole.

The most efficient point when corrective action should be considered or performed is rarely near or after the failure state has occurred. For many components, repair early in the lifecycle, and well before failure, can extend life and avert expensive damage caused by accelerated degradation later. The point at which corrective repair action is most efficient is termed the “sweet spot” for corrective action. In order to identify this sweet spot for a component, a condition assessment method and metric must be used. One such approach is the Building Condition Index (BCI) metric (Uzarski, 1997) which objectively represents building component condition on a scale from 0-100 (Table 1).

Experience with the building component CI metric has shown that for a wide variety of components, the repair sweet spot falls in a CI range of 75-85. Performing repairs at the sweet spot can result in penalty cost savings from major repair or replacement due to costly critical failure consequences later in the lifecycle. Thus, the total cost of facility ownership is decreased by accurately timing necessary repairs and replacement of components over the lifespan of the building. The proposed model will address the optimized timing for these repairs.

Table 1. Condition Index Definitions

Condition Index	Definition
100-85 Good	Slight serviceability/reliability reduction overall to component.
85-70 Satisfactory	Component serviceability/reliability is degraded but adequate.
70-55 Fair	Component serviceability or reliability is noticeably degraded
55-40 Poor	Component has significant serviceability or reliability loss.
40-25 Very Poor	Unsatisfactory serviceability or reliability reduction
25-10 Serious	Extreme serviceability or reliability reduction
10-0 Failed	Overall degradation is total.

Building Component Attributes

To determine the necessary major repairs and component replacements in a building, and to justify the timing of that work to optimize the savings per repair dollar invested, a building component model is defined. This model is constructed by creating an inventory of components that comprise the building. The building component inventory divides the facility first into major building systems, and then into the individual components that make up those systems. This classification is based on the ASTM Uniformat II hierarchy (ASTM E 1557-02). Each component in the building model also has assigned attributes based on its material, type, age, and location. For example, a window (component) may be made of metal, vinyl, or wood. The different material types have different responses to their environment over time, have different expected service lives, and require different work actions at various stages in their lifecycle. There is also separate repair and replacement cost information related to labor, materials, and equipment associated with each component type. Therefore, the building component with its associated attribute information is the basic unit for building lifecycle asset management and condition tracking. Table 2 shows a small subset of the building inventory data used to construct the simulated building component model for this analysis.

Table 2. Building Model Component Inventory List

System	Component	Type	Qty	UM	Replace Cost ($)	Service Life (yr)
Electrical	Distribution	Electrical Category 1	13,000	SF	$47,151	75
Electrical	Lighting Fixtures	Fluorescent Interior	425	EA	$144,840	30
Electrical	Generator Set	Gasoline 11.5-35 KW	1	EA	$2,418	25
Exterior	Exterior Door	Glass Personnel	6	EA	$17,410	40
Exterior	Exterior Window	Metal Casement	57	EA	$53,921	40
Interior	Interior Ceiling	Acoustical Suspended	3,259	SF	$22,487	35
Interior	Interior Door	Metal Personnel	87	EA	$86,559	75
Interior	Interior Wall	Masonry Concrete Block	10,391	SF	$176,959	30
Plumbing	Waste Piping	Vinyl/Plastic	220	LF	$4,484	75
Plumbing	Piping (Plumbing)	Copper 1"-2" Pipe	440	LF	$7,968	75
Structural	Slab	Concrete Foundation	13,000	SF	$82,680	100
Structural	Strip Footing	Concrete	617	LF	$59,966	150
Structural	Roof Deck	Metal	13,000	SF	$72,540	75
Roofing	Roof Drainage	Aluminum Gutter	617	LF	$12,574	25
Roofing	Roof Insulation	Perlite Rigid	13,000	SF	$28,990	75

The service life of a component reflects the average expected time that a component will perform as required in service before a replacement is needed. Initially, each building component has an expected condition deterioration trend, which relates the projected condition index metric of the component as a function of its time in service. Periodic inspections are performed to measure the actual in service condition index of the component based on the distresses that are observed. This condition assessment process results in a measured condition index which is used to calibrate the condition deterioration trend based on inspection observations (Grussing, 2006). The condition index, CI, is expressed as a function of the time in service, t, using the Weibull reliability model, expressed as:

$$CI = A \times e^{-(\frac{t}{\beta})^{\alpha}}$$

Condition deterioration factors A, alpha, and beta are determined uniquely for a component based on the component type and inspection calibration information. In addition to predicting the future condition of a component, this model provides the basis for calculating the extended service life that results when a corrective work action is performed by corrective repair or total replacement of the component. Corrective repair improves the condition of the component and is usually initiated sometime prior to failure. Corrective repair is different from a major overhaul or component replacement because it does not usually correct all component distresses. Some minor and inherent distresses will remain part of the component until it is completely replaced. Therefore, after a repair is completed, the model assumes the CI value is improved to 95 (out of 100), which relates to a full restoration of serviceability on the CI scale, but not necessarily a pristine condition. The model also assumes that the condition deterioration rate at a given condition index level are the same before and after a repair. Therefore, corrective repair essentially shifts the condition lifecycle curve to the right, thus extending service life. Figure 1 shows the projected condition index plotted versus time for the typical building window component. The discontinuity at time, t = 20 years, represents a corrective repair event.

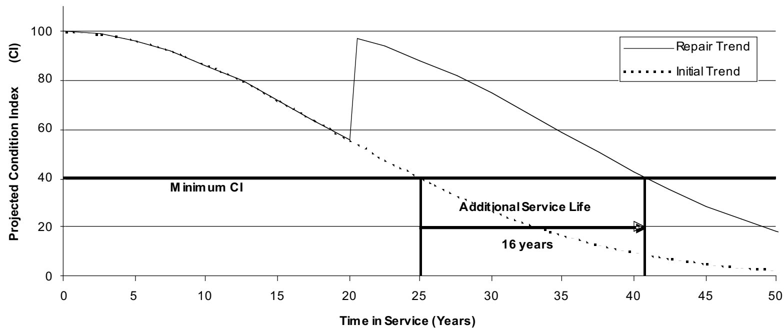

Figure 1. Component Condition Prediction Trend for Metal Window Example

Based on the definition of the CI scale, functional component failure occurs when the CI falls to approximately 40, which establishes a performance threshold limit for the model. For the unrepaired component lifecycle model, CI = 40 when the time in service equals the expected service life. For a component that has been repaired, the improved condition results in additional service life, as illustrated by Figure 1. Thus, the benefit of repair allows the deference of capital renewal required from component failure.

Eventually, however, a component will likely require complete replacement. In the condition lifecycle model, complete component replacement essentially resets the component service life clock and the component CI is restored to its maximum (CI=100).

Model Framework

Parametric Component Repair Cost

A parametric model of component repair cost is used to quickly estimate the corrective repair cost as a percentage of the total replacement cost based on the condition index value. As a building component's condition as represented by the condition index deteriorates, the cost of repair to restore full serviceability increases. The parametric cost model assumes that when the condition index is near 100, repair cost is minimal. Likewise, when the condition index is at or below the failure threshold (CI = 40), the cost to repair is equal to the replacement cost since repair is no longer an economically viable option. Between these CI values, the estimated unit repair cost is described by the parametric equation:

$$UC_{repair} = UC_{replace} \times \left(\frac{100 - CI}{100 - CI_{term}}\right)^N$$

Where:

- UC_{repair} = estimated unit repair cost as a function of condition
- $UC_{replace}$ = estimated unit replacement cost
- CI = current predicted condition index
- CI_{term} = designated Condition Index terminal value, taken as 40
- N = cost escalation factor

The unit replacement cost is based on component unit price source information, and sets a maximum limit on the repair estimate. Likewise, any repair service call will have a minimum repair cost for a technician or repair worker to initiate work at the site. The parameter N has been determined for various building components by comparing the cost of a range of repair work actions at different lifecycle points to the condition based distresses and resulting CI values associated with those work actions. Information for a metal window component with a unit replacement cost of $1000 and a minimum service call cost of $50 is tabulated in Table 3 and displayed graphically in Figure 2. Based on a best fit of the parametric cost equation above, the parameter N is determined to be 2.4 for this window component, and is determined in a similar fashion for other building components.

Table 3. CI for various work actions, example metal window component

Observed Condition	CI	Work Action	Cost
Displaced sash	90	Readjust sash	$84
Damaged Trim	84	Replace interior trim	$110
Cracked Glass	76	Replace glass	$185
Operationally Impaired Sash	60	Replace sash	$312
Damaged Trim/Sash	50	Replace sash and trim	$705
Total Deterioration	40	Replace frame, sash, and trim	$1000

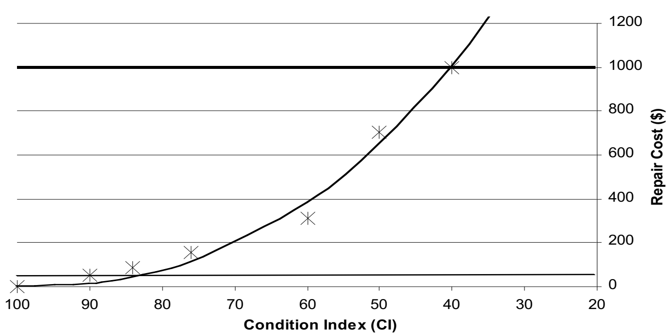

Figure 2. Unit Repair Cost ($) as a function of condition index (CI)

Economic Model

In order to evaluate the economic merit of different building component repair or replacement alternatives, a Savings-to-Investment Ratio (SIR) approach is taken. This economic model is chosen over other economic metrics because; 1) each alternative results in an individual ratio that indicates the economic performance of that work action, 2) the model accounts for the discount rate of money, and 3) alternatives with different time horizons or service lives can be compared appropriately (ASTM E 964-02). To account for the time value of money, a discount rate of 5% is used in this analysis, and all savings and investments are expressed in discounted present value terms.

The SIR is calculated as:

$$SIR = \frac{S_t/(1+i)^t}{I_r/(1+i)^r}$$

Where:

S_t = Savings, amortized replace cost times additional service life
I_r = Investment, cost of replacement or parametric cost of repair
t = year savings is realized, based on year unrepaired component is failed
r = year repair or replacement action is performed
i = discount rate, 5%

For a repair action, the investment is the parametric estimate of repair cost based on the condition index at year r. The savings is calculated as the deferment of amortized replacement cost (Unit Replace Cost / Design Life) multiplied by the additional service life gained by the repair and obtained by the condition prediction trend model. This savings is realized in year of expected failure if no repair was performed. Table 4 presents the SIR for repair at various condition index values for the metal window component example.

For a replacement action, the investment is the unit replacement cost in the year it is being replaced. Based on similar logic for the repair savings, the replacement savings is calculated as the amortized replacement cost (Unit Replace Cost / Design Life) multiplied by the design service life. If the component is replaced at failure (CI=40) and no other collateral savings result, the repair SIR is equal to one. This establishes the baseline investment strategy of replacement when failure occurs.

Table 4. SIR Analysis for various repair CI triggers

Repair CI	Repair Year	Repair Cost	Investment (Discount)	Add'l Life (Yrs)	Savings	Savings (Discount)	SIR
90	8.5	$50	$33	2.6	$102	$30	0.92
85	10.5	$50	$30	4.6	$185	$54	1.82
80	12.3	$72	$39	6.4	$257	$76	1.93
75	14.0	$122	$62	8.1	$324	$96	1.55
70	15.6	$189	$89	9.7	$387	$114	1.29
60	18.7	$378	$152	12.8	$510	$151	0.99
40	25.0	$1,000	$295	19.1	$763	$225	0.76

Based on results in Table 3, Figure 3 illustrates the optimal repair occurs when CI is 80, where a SIR of nearly 2 results. In addition, the graph illustrates that repair of the component below a condition index of 60 is not an economically attractive option when compared to replacement at failure because the SIR is below 1.0. Therefore, if CI < 60, replacement near the CI terminal value of 40 should instead be planned. Note that if replacement of the component also resulted in lower operations costs due to energy cost savings, for example, these additional savings would result in a replacement SIR greater than 1, and repair would have to be performed at an even higher CI to be economically attractive.

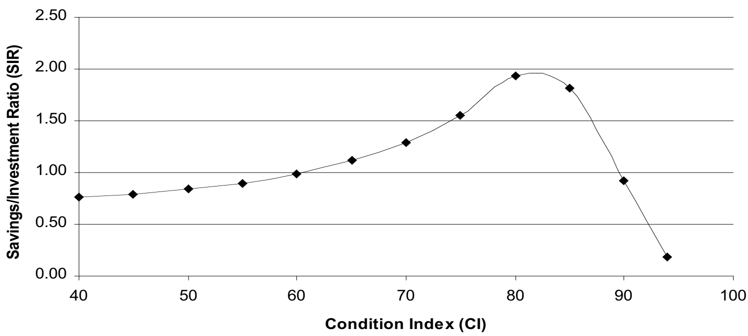

Figure 3. Optimal repair CI to maximize Savings to Investment Ratio (SIR)

Model Simulation Results

Using the results above, a long term maintenance, repair, and capital renewal plan can be developed for an organization managing a portfolio of several buildings with hundreds of building components in each, all at varying condition states. Using a structured economic analysis framework, the SIR can be estimated for each unique component, and the most attractive building investments can be identified. A model simulation was performed to illustrate the benefits of this approach.

A typical 13,000 square foot post office facility was modeled using component data from RS Means (RS Means, 2004). Performing simulation analysis over a 50-year lifecycle to project conditions and work requirements, the two scenarios described above were analyzed under the following conditions:

1) Run to Failure – Intermediate corrective repairs are ignored and components deteriorate to the failure point, at which time they are replaced at the replacement cost. A replacement work action is generated when the CI falls below the threshold performance limit indicating the failure point, CI<40.
2) Best-Practice – Component conditions are monitored and repairs are performed if economical based on the estimated SIR of the work action. The model is set to consider intermediate correct action when the component CI reaches the previously established repair "sweet spot", CI < 80. At this point,

a repair work action and associated repair work cost is generated, resulting in a condition index improvement and service life extension.

Figure 4 below show the total cumulative lifecycle costs results over a 50 year period for each of the two options. Each jump in the graph represents repair or replacement work accomplished in that respective year. The results of this model predict $940,000 in component repair/replacement over the lifecycle with the Run-to failure approach, versus $520,000 with condition monitoring and timed repair actions. This 45% lifecycle cost reduction estimate only reflects facility maintenance, repair, and restoration costs. It does not reflect user costs due to unexpected downtime of failed components and systems, which can add considerably more to the Run-to failure option.

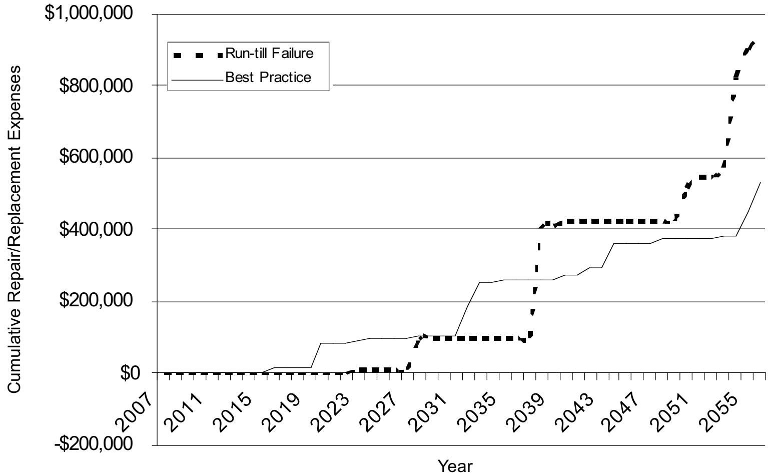

Figure 4. Simulated Cumulative Lifecycle Cost over 50-Year Period

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